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# Indoor Throughput and Range Improvements using Standard Compliant AP Antenna Diversity in IEEE 802.11a and ETSI HIPERLAN/2

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**Abstract** - This paper explores the application of space-time diversity techniques to enhance the performance of 5 GHz WLANs. The analysis is based on systems conforming to either the IEEE 802.11a or ETSI HIPERLAN/2 standard. Two antennas are assumed at the Access Point (AP) with a single antenna at the Mobile Terminal (MT). Down-Link (DL) improvements are offered via the application of one of two fully compliant diversity schemes. The first technique can be applied to Time Division Duplex (TDD) OFDM systems (i.e. HIPERLAN/2) and is based on adaptive sub-band phase compensation. The second technique can be applied to non-TDD systems (i.e. 802.11a) and makes use of spatial transmit delay diversity. Up-Link (UL) improvement is offered via the use of spatial receive diversity with maximal ratio sub-band combining. Software simulated Physical (PHY) layer Packet Error Rate (PER) results are presented for the various methods and compared with those of an unaided transceiver. Combining the enhanced link level results with an analysis of the 802.11a and HIPERLAN/2 protocols, the expected throughput and range enhancements for both standards are computed.

## I. INTRODUCTION

ETSI HIPERLAN/2 [1,2] and IEEE 802.11a [3,4] are two WLANs standards that will operate in the 5 GHz band and provide data rates of up to 54 Mbps.

The physical (PHY) layers [1,3] of both standards are similar and based on the use of Coded Orthogonal Frequency Division Multiplexing (COFDM). Importantly, the physical layer provides several operating modes, each with different modulation schemes and coding rates. These are selected by a link adaptation scheme. A detailed description of the PHY layer can be found in [5]. Although only minor differences exist between the two physical layers [5-7], significant differences can be found in their Medium Access Control (MAC) protocols.

The IEEE 802.11a standard uses a distributed access scheme where mobile terminals (MT) compete with one another to access the radio medium. In the ETSI HIPERLAN/2 standard, a centralised Time Division Multiple Access (TDMA) approach is adopted. There is no need to include protocol specific fields in the OFDM frame format since the length and rate are determined in the MAC. This enables the Access Point (AP) to allocate radio resources for individual MTs [8].

This paper analyses the performance of a number of diversity schemes for use with 802.11a and HIPERLAN/2. We assume the use of two spaced antennas at the AP and a single antenna at the MT. For the Down-Link (DL), two forms of transmit diversity are considered. The first technique is applicable to Time Division Duplex (TDD) systems (i.e. HIPERLAN/2) and uses adaptive sub-band phase compensation. The second technique does not require a TDD structure (i.e. it is

suitable for 802.11a) and makes use of spatial transmit delay diversity. For the Up-Link (UL), we consider the use of spatial receive diversity with sub-band maximal ratio combining. Packet Error Rate (PER) results are presented for both the transmit and receive diversity methods and are compared with those of an unaided transceiver. Combining these enhanced link level results with an analysis of the 802.11a and HIPERLAN/2 protocols we compute the expected throughput and range enhancement for both standards independently for the UL and DL.

The paper is organised as follows. Section II elaborates further on the differences between the two standards. Section III introduces the concept of phase compensation and transmit delay diversity and explains their significance to each standard. PER and throughput versus range results are presented in sections IV and V. Finally, the paper concludes by comparing and discussing the performance of the two diversity-enhanced standards.

## II. MEDIUM ACCESS CONTROL

### A. IEEE 802.11a MAC

The main differences between IEEE 802.11a and ETSI HIPERLAN/2 occur in the MAC. The IEEE 802.11 standardisation group has specified a common MAC mechanism for IEEE 802.11, IEEE 802.11a, and IEEE 802.11b that is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [4].

An MT must sense the medium for a specific time interval and only if the medium is idle can it start to transmit a packet. Otherwise, the transmission is deferred and a back-off process begins, which requires the terminal to wait for a given time interval. Once this back-off time has expired, the terminal can attempt to access the medium once again [9-11]. Since a collision in the wireless environment is undetectable, a positive acknowledgement is used to notify that a frame has been successfully received. If this acknowledgement is not received, the terminal will retransmit the packet.

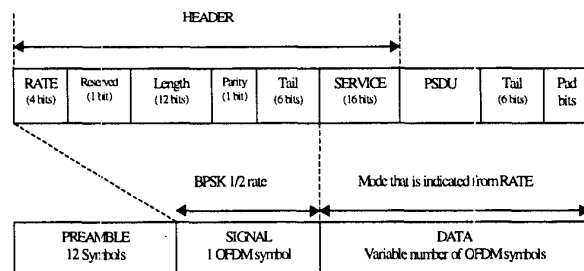


Fig. 1. PPDU Frame Format

The Physical Layer Convergence Procedure (PLCP) maps a MAC PDU into a frame format. Fig. 1 shows the format of a complete packet (PPDU) in 802.11a, including the preamble, header and Physical Layer Service Data Unit (PSDU or payload). The header contains information about the length of the payload and the transmission rate. The length field takes a value between 1 and 4095 and specifies the number of bytes in the PSDU.

### B. ETSI BRAN HIPERLAN/2 MAC

In the ETSI HIPERLAN/2 standard the medium access is based on a TDD/TDMA approach using a MAC frame with a period of 2ms [2]. The control is centralised to an AP, which informs the MTs at which point in the MAC frame they are allowed to transmit their data. Time slots are allocated dynamically depending on the need for transmission resources.

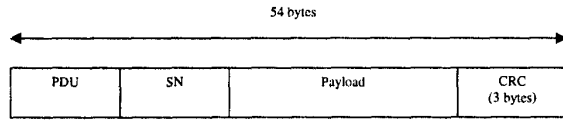


Fig. 2. Format of the long PDUs

DL, UL and direct-link phases consist of two types of PDU: long PDUs and short PDUs. Long PDUs (Fig. 2) have a size of 54 bytes and contain control or user data. The payload is 48 bytes with the remaining data used for the PDU type, a sequence number (SN) and a cyclic redundancy check (CRC-24). Long PDUs are referred to as the long transport channel (LCH).

### III. PHASE COMPENSATION VERSUS TRANSMIT DELAY DIVERSITY

In this section two transmit diversity techniques are explored. These methods are ideal for use in the DL of a WLAN standard since they enable a diversity gain to be realised for unmodified MTs with a single antenna.

Phase compensation is a technique whereby the sub-band phases of two spatially separated transmit signals are manipulated to ensure their constructive addition at the receiver. This method relies on a-priori knowledge of the spatially separated radio channels.

A transmit delay diversity scheme synthetically enhances the channel by deliberately introducing delay spread, thus generating a highly frequency selective channel. Of course, the maximum potential of this scheme is only realised for channels with low delay spreads. The resulting frequency diversity can then be exploited by the appropriate use of FEC in the MT. In this technique, a-priori knowledge of the radio channel is not required [13].

In this paper, unlike in [14], we propose that the UL Channel State Information (CSI) vector from each of the spatially separated AP antennas is used to pre-rotate the subsequent DL transmissions. Since HIPERLAN/2 operates using a TDD MAC scheme, we can expect contiguous UL/DL transmissions over a stream of 2 ms slots. Hence, for the DL of HIPERLAN/2, phase compensation appears to be a natural choice.

For 802.11a the use of transmit delay diversity appears more suitable since there is no guaranteed time structure to the UL/DL transmissions. Hence, given the ad-hoc

nature of the 802.11a network, it is not possible to ensure that an UL transmission has occurred within the channel's coherence time (and hence valid CSI estimates exist).

Fig. 3 and Fig. 4 illustrate the block diagrams for the proposed dual antenna transmit diversity systems.

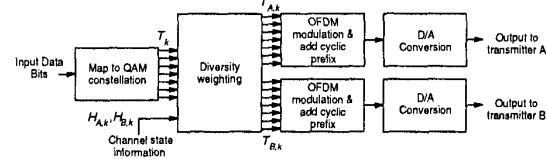


Fig. 3. Transmit DL Diversity applied to HIPERLAN/2

In Fig. 3, two signal streams are modulated and transmitted separately. The sub-band phases are compensated accordingly at each antenna, based on conjugate of the CSI vector extracted from the most recently received UL transmission.

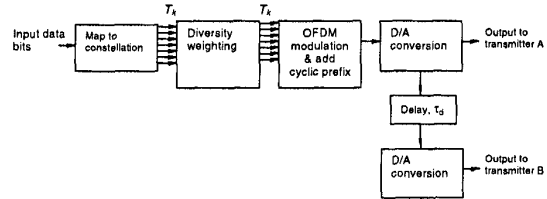


Fig. 4. Transmit DL Diversity applied to 802.11a

In Fig. 4, only one signal stream needs to be generated. However, the signal is then transmitted separately from spatially separated antennas with a pre-determined and deliberate time delay introduced.

### IV. PER RESULTS

In this section, the deployment of compliant diversity schemes are analysed for both UL and DL modes. Software simulated PER results are presented to determine the gains achieved in both standards.

Table 1: PHY Layer Modes

Mode	Modulation	Coding Rate	Bit rate [Mb/s]
1	BPSK	1/2	6
2	BPSK	3/4	9
3	QPSK	1/2	12
4	QPSK	3/4	18
5 <sup>1</sup>	16QAM <sup>1</sup>	1/2	24
5 <sup>2</sup>	16QAM <sup>2</sup>	9/16	27
6	16QAM	3/4	36
7	64QAM	3/4	54

<sup>1</sup>IEEE 802.11a only, <sup>2</sup>ETSI BRAN HIPERLAN/2 only

A typical Non-Line-of-Sight (NLOS) indoor office environment is assumed for these simulations. All results are based on soft Viterbi decoded PHY bursts sent over a statistically large set of channels that conform to the ETSI/IEEE specified channel model 'A' [12]. Each antenna is used to either transmit or receive and experiences the same average fading profile. The channel impulse response taps for the two spatially separated AP antennas are subject to independent and

uncorrelated Rayleigh fading. In the transmit diversity mode, we assumed that each of the two antennas is fed with half the power associated with a single antenna solution. Table 1 shows the PHY layer modes used in the software simulation.

#### A. Transmit Diversity in the Down Link (DL)

The TDD nature of the HIPERLAN/2 MAC is of fundamental importance to the phase compensation diversity technique since the UL and DL share the same frequency spectrum. We thus assume that the nature of the physical channel is the same for both UL and DL transmissions. Of course, this will not be the case and knowledge of the CSI from DL transmissions, at the time of UL, will be inaccurate [14].

Channel time variations were modelled using a classic Jake's Doppler spectrum corresponding to a terminal speed of 3 m/s on each tap of the channel impulse response. In the phase compensation simulations, a delay of 2ms between the DL and UL transmissions was assumed to take into account the time decorrelation of the CSI vectors. In the transmit delay diversity simulations, a time delay of 400ns (50% of the available guard interval) was chosen to increase the average root mean squared (rms) channel delay spread from 50ns to 206ns [13]. A payload size of 1500 bytes is assumed for the 802.11a transmissions.

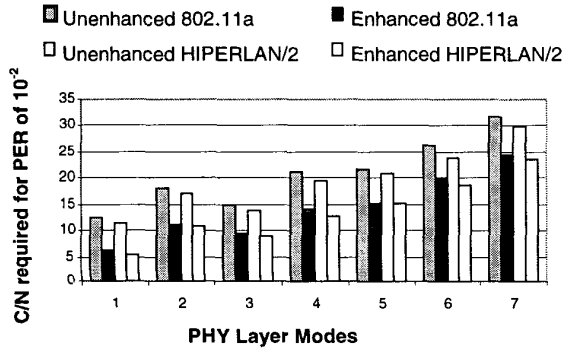


Fig. 5. DL C/N required to achieve a PER of  $10^{-2}$  with and without transmit delay diversity for both standards

From Fig. 5, it can be seen that the DL C/N required for a PER of  $10^{-2}$  using transmit diversity is improved by around 5-7 dB. The improvements offered by transmit delay and phase compensation are near identical. In many cases, the use of transmit diversity enables the use of a higher modulation mode for the same PER performance. The PER of 802.11a is slightly worse than that of HIPERLAN/2 because of its use of larger data payloads in its MAC [15].

#### B. Receive Diversity in the Up Link (UL)

Fig. 6 illustrates the performance of dual antenna diversity on the UL. Transmit diversity cannot be applied here since the MT only has a single antenna. The signals received on each AP antenna (labelled A and B) are demodulated separately. It is assumed that the demodulation processing includes time and frequency synchronisation and the formation of CSI vectors for each channel,  $H_{A,k}$  and  $H_{B,k}$ , which in the case of HIPERLAN/2 can be used in the subsequent DL transmission. The received data vectors from the

antennas,  $R_{A,k}$  and  $R_{B,k}$ , are then combined into a single stream  $R_k$ , using maximal ratio combining. The data is then passed through soft Viterbi decoding.

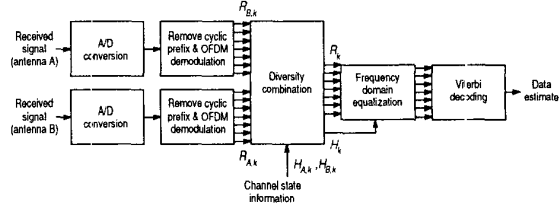


Fig. 6. Space Diversity UL Configuration for 802.11a and HIPERLAN/2

The results presented here also assume a payload size of 1500 bytes for the 802.11a transmission.

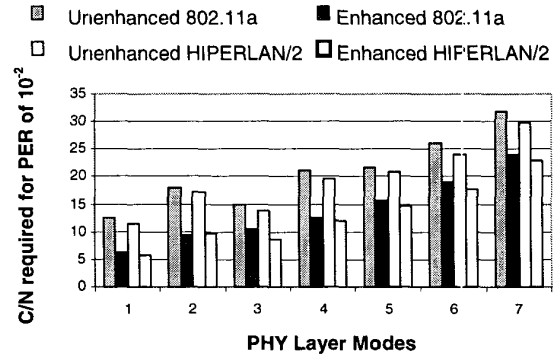


Fig. 7. UL C/N required to achieve a PER of  $10^{-2}$  with and without receive diversity for both standards

Compared to transmit delay diversity (see Fig. 5), similar (slightly better) performance gains are shown in Fig. 7 for a receiver incorporating sub-band maximal ratio combining at the receiver. Again, substantial gains of between 5 and 8 dB are achievable for both standards. Again, this implies that a higher modulation mode could be chosen using diversity in the UL mode for an equivalent PER performance. Alternatively, this gain could be translated into battery power savings at the MT (which is likely to be a portable device). Assuming PHY layer mode 4 (see Table 1), a power saving of 7 dB and 8 dB can be realised for 802.11a and HIPERLAN/2 respectively. The selection of a higher modulation mode would also enable an MT to transmit its data while consuming less time in the PDU, thus increasing network capacity.

#### V. THROUGHPUT RESULTS

In this section, a more detailed analysis of the diversity schemes reported in section III will be presented in terms of data throughput and operating range. The simple throughput approximation [15] shown in equation (1) is used [15].

$$\text{Throughput} = R * (1 - \text{PER}) \quad (1)$$

where R represents either the link or system bit rate and PER is the packet error rate for a specific PHY layer mode. To map the C/N ratio to an expected operating range, a simple path loss equation is required. The equation shown below is used:

$$L_p = 10 \log_{10} \left( \frac{4\pi d}{\lambda} \right)^2 + \alpha d \quad (2)$$

where  $d$  (in metres) represents the distance between the AP and MT,  $\lambda$  the wavelength and  $\alpha$  (in dB/m) the additional clutter loss. In the following sections,  $\alpha$  is assumed to take a value of 0.5 dB/m. The maximum indoor transmit power is assumed to be 23 dBm and the receiver sensitivity is set at -85 dBm.

#### A. Transmit Diversity in the Down Link (DL)

Fig. 8 and Fig. 9 are upper-bound link and system throughputs based on a C/N driven link adaptation mechanism (the link throughput does not compensate for the MAC overhead, which has been shown to effect 802.11a more than HIPERLAN/2 [15]). For each value of distance, the PHY mode offering the highest throughput is chosen based on the estimated C/N.

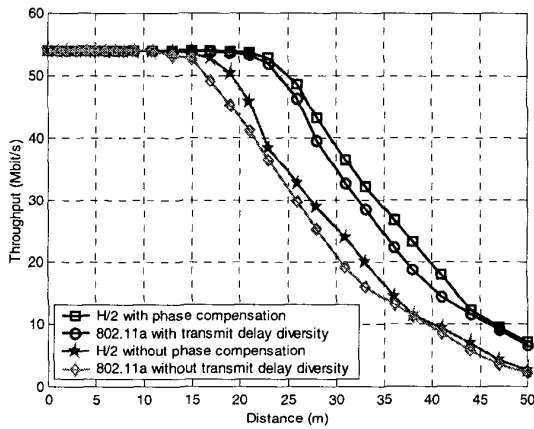


Fig. 8. Link throughput (DL) versus range with and without transmit diversity

A PSDU size of 1500 byte was chosen to achieve an optimal trade-off between overhead efficiency and PER performance [5]. By using transmit delay diversity, the link and system throughput is increased for both systems.

For a distance of 25 m, the link throughput for 802.11a is increased from 32 Mb/s to 48 Mb/s. For HIPERLAN/2, the link throughput is increased from 35 Mb/s to 51 Mb/s. At a distance of 40m, the HIPERLAN/2 link rate is increased from 10 Mb/s to 20 Mb/s, while 802.11a link rate is increased from 9 Mb/s to 16 Mb/s.

Fig. 9 incorporates the overheads of the MAC protocol to estimate the system throughput. Again, for a distance of 25m, the link throughput for 802.11a is increased from 21 Mb/s to 27.5 Mb/s. For HIPERLAN/2, the link throughput is increased from 27 Mb/s to 48 Mb/s. At a distance of 40 m, the HIPERLAN/2 link rate is increased from 8 Mb/s to 15 Mb/s, while 802.11a link rate is increased from 7.5 Mb/s to 12 Mb/s.

For the noise limited single user scenario considered here, HIPERLAN/2 can be seen to outperform 802.11a. For both systems, transmit diversity is shown to result in significant DL improvements.

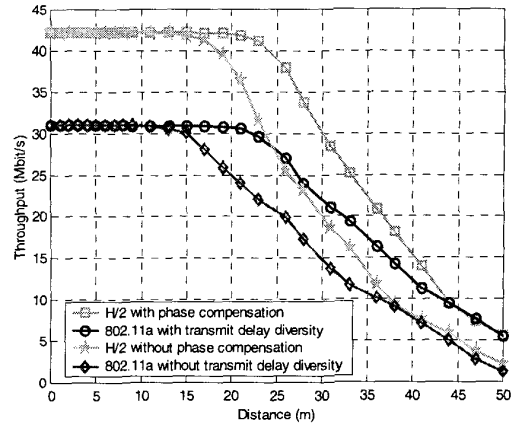


Fig. 9. System throughput (DL) versus range with and without transmit diversity

#### B. Receive Diversity in the Up Link (UL)

Fig. 10 and Fig. 11 shows the link and system throughput versus distance for UL transmissions with and without maximal ratio receive diversity. Results are similar to those seen on the DL, with throughput generally within 1 to 2 Mb/s of their UL equivalent.

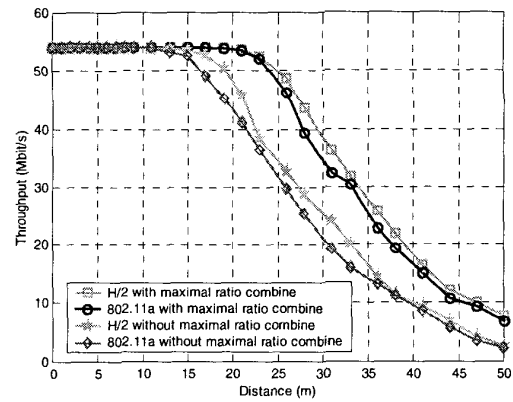


Fig. 10. Link throughput (UL) versus range with and without receive diversity

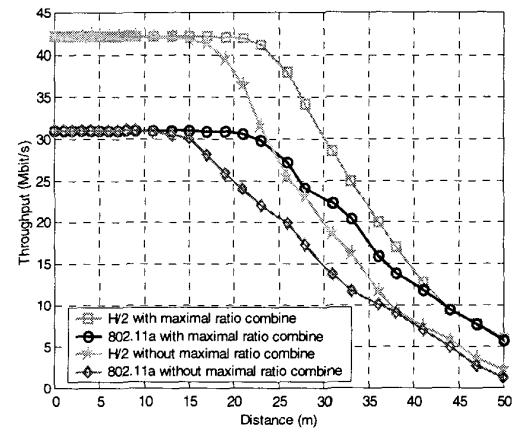


Fig. 11. System throughput (UL) versus range with and without receive diversity

Standard receive diversity at the AP has been shown to improve UL throughput. However, it should be noted that the DL throughput is generally considered to be more important. For systems using diversity exclusively at the AP, transmit diversity is shown to be a powerful method for improving performance. Similarly, to claim range extension it is necessary to improve *both* the UL and DL simultaneously.

Fig.12 compares the DL and UL throughputs at a range of 30 m for the two standards with and without diversity. For 802.11a, the preferred configuration uses transmit delay diversity on the DL (providing the delay spread is low) and maximal ratio receive diversity on the UL. For HIPERLAN/2, phase compensation is applied on the DL and maximal ratio receive diversity on the UL. Using these configurations, link throughputs at 30 m are significantly increased, with gains of around 13 Mb/s on the UL and DL.

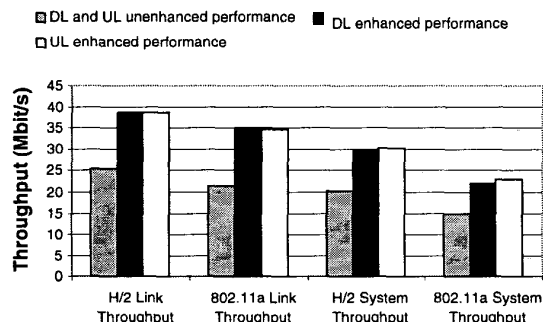


Fig. 12. Throughput link enhancements for UL and DL (30m range)

## VI. CONCLUSIONS

This paper has studied the application of antenna diversity at the AP for IEEE 802.11a and ETSI HIPERLAN/2. The analysis was performed using the ETSI/IEEE specified channel model A (typical office). PER, link and system throughput results were presented for the UL and DL of both standards.

For 802.11a, the preferred configuration used transmit delay diversity on the DL (providing the delay spread is low) and maximal ratio receive diversity on the UL. For HIPERLAN/2, phase compensation is applied on the DL with maximal ratio receive diversity on the UL. One drawback of phase compensation is its requirement for a-priori channel knowledge, which prevents application in 802.11a. Although receive diversity was applied on the UL, in practice the use of transmit diversity could also be used here, however this would require diversity antennas to be mounted on the MT.

From a complexity standpoint, transmit delay diversity only requires the additional transmission of a time delayed signal replica. Phase compensation requires the generation of two independent waveforms. Hence, transmit delay diversity removes the additional overhead of diversity weighting, Fast Fourier Transform (FFT) processing and modulating on the second antenna. While this sounds significant, the AP require two independent FFT processors in order to implement UL maximal ratio receive diversity.

Although delay transmit diversity was found to offer an inferior performance compared to phase compensation, the difference was less than 1 dB for all PHY layer modes. Results in this paper have only been generated for channels with low rms delay spreads. For large delay spreads, transmit delay diversity will degrade performance. Knowledge of the rms delay spread on each link must be stored at the AP for this scheme to operate efficiently in environments with mixed rms delay spreads. As mentioned, phase compensation has the advantage of application in all channel conditions.

In conclusion, results have shown that for both 802.11a and HIPERLAN/2, antenna diversity at the AP can realise significant improvements in throughput (in some cases almost doubling the available bit rate). Alternatively, these gains can be used to enhance operating range or reduce power consumption in battery operated MTs.

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